VISIT…

4 Preventive Maintenance

INTRODUCTION

Preventive maintenance (PM) is an important component of a maintenance activity. Within a maintenance organization it usually accounts for a major proportion of the total maintenance effort. PM may be described as the care and servicing by individuals involved with maintenance to keep equipment/facilities in satisfactory operational state by providing for systematic inspection, detection, and correction of incipient failures either prior to their occurrence or prior to their development into major failure.[1] Some of the main objectives of PM are to: enhance capital equipment productive life, reduce critical equipment breakdowns, allow better planning and scheduling of needed maintenance work, minimize production losses due to equipment failures, and promote health and safety of maintenance personnel.[2]

From time to time PM programs in maintenance organizations end up in failure (i.e., they lose upper management support) because their cost is either unjustifiable or they take a significant time to show results. It is emphasized that all PM must be cost-effective. The most important principle to keep continuous management support is: "If it is not going to save money, then don't do it!"

This chapter presents important aspects of PM.

PREVENTIVE MAINTENANCE ELEMENTS, PLANT CHARACTERISTICS IN NEED OF A PM PROGRAM, AND A PRINCIPLE FOR SELECTING ITEMS FOR PM

There are seven elements of PM as shown in Fig. 4.1.[1] Each element is discussed below.

1. *Inspection:* Periodically inspecting materials/items to determine their serviceability by comparing their physical, electrical, mechanical, etc., characteristics (as applicable) to expected standards
2. *Servicing:* Cleaning, lubricating, charging, preservation, etc., of items/materials periodically to prevent the occurrence of incipient failures
3. *Calibration:* Periodically determining the value of characteristics of an item by comparison to a standard; it consists of the comparison of two instruments, one of which is certified standard with known accuracy, to detect and adjust any discrepancy in the accuracy of the material/parameter being compared to the established standard value

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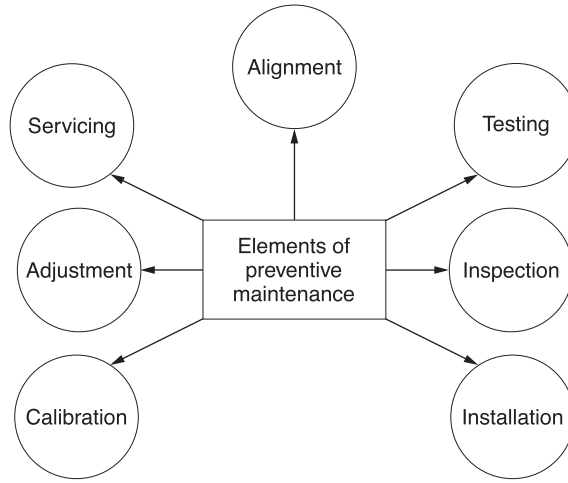

FIGURE 4.1 Elements of preventive maintenance.

4. *Testing:* Periodically testing or checking out to determine serviceability and detect electrical/mechanical-related degradation
5. *Alignment:* Making changes to an item's specified variable elements for the purpose of achieving optimum performance
6. *Adjustment:* Periodically adjusting specified variable elements of material for the purpose of achieving the optimum system performance
7. *Installation:* Periodic replacement of limited-life items or the items experiencing time cycle or wear degradation, to maintain the specified system tolerance

Some characteristics of a plant in need of a good preventive maintenance program are as follows:[2]

- Low equipment use due to failures
- Large volume of scrap and rejects due to unreliable equipment
- Rise in equipment repair costs due to negligence in areas such as regular lubrication, inspection, and replacement of worn items/components
- High idle operator times due to equipment failures
- Reduction in capital equipment expected productive life due to unsatisfactory maintenance

Table 4.1 presents 17 questions for determining the adequacy of a preventive maintenance program within an organization.

The answer "yes" or "no" to each question is given 5 or 0 points, respectively. A "maybe" answer is assigned a score from 1 to 4. A total score of less than 55 points indicates that the preventive maintenance program requires further improvements.[2]

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TABLE 4.1
Preventive Maintenance Program Evaluation Questions

No.	Question	Answer		
		Yes (5 points)	Maybe (1–4 points)	No (0 points)
1	Is the trend in downtime recorded and reported regularly?			
2	Is there a formal PM program in place?			
3	Are inspectors performing their inspection duties full-time?			
4	Are check sheets controlled to assure 100% compliance?			
5	Are inspection routes developed/scheduled on the basis of work measurement methods?			
6	Are inspection reports randomly checked by supervisor to determine their accuracy?			
7	What percentage of downtime is due to maintenance?	(≥ 8%)	(8% ≤)	(Unknown)
8	Is the lubrication task performed through the scheduled usage of check sheets?			
9	Does maintenance management receive meaningful downtime reports?			
10	Is one individual responsible for the overall PM?			
11	Were lubrication routes developed and scheduled on the basis of time and method studies?			
12	Is data processing used to schedule and report PM inspections and lubrication?			
13	Are foreseeable problems, discovered through PM inspections, quickly reported?			
14	Is PM work highlighted in the cost-reporting system to permit routine analysis of PM as a distinct class of expenditure?			
15	Are lubrication requirements examined regularly to minimize the need for different types of lubricants?			
16	Is the analysis of breakdown reports performed to detect failure patterns that can be rectified by adjusting the PM program?			
17	Are plant/building assets examined regularly as an integral part of the formal inspection program?			

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References 4 and 5 proposed the following principle or formula to be used when deciding to go ahead with a PM program:

$$(\mathrm{NB})(\mathrm{ACPBD})(\alpha) > \mathrm{CPMS} \tag{4.1}$$

where

CPMS = total cost of preventive maintenance system,
α = a factor whose value is proposed to be taken as 70%; more specifically, 70% of the total cost of breakdowns,
NB = number of breakdowns,
ACPBD = average cost per breakdown.

IMPORTANT STEPS FOR ESTABLISHING A PM PROGRAM

To develop an effective PM program, the availability of a number of items is necessary. Some of those items include accurate historical records of equipment, manufacturer's recommendations, skilled personnel, past data from similar equipment, service manuals, unique identification of all equipment, appropriate test instruments and tools, management support and user cooperation, failure information by problem/cause/action, consumables and replaceable components/parts, and clearly written instructions with a checklist to be signed off.[6]

There are a number of steps involved in developing a PM program. Figure 4.2 presents six steps for establishing a highly effective PM program in a short period. Each step is discussed below.[3]

1. *Identify and choose the areas.* Identify and selection of one or two important areas to concentrate the initial PM effort. These areas should be crucial to the success of overall plant operations and may be experiencing a high degree of maintenance actions. The main objective of this step is to obtain immediate results in highly visible areas, as well as to win concerned management support.
2. *Identify the PM needs.* Define the PM requirements. Then, establish a schedule of two types of tasks: daily PM inspections and periodic PM assignments. The daily PM inspections could be conducted by either maintenance or production personnel. An example of a daily PM inspection is to check the waste water settleable solids concentration. Periodic PM assignments usually are performed by the maintenance workers. Examples of such assignments are replacing throwaway filters, replacing drive belts, and cleaning steam traps and permanent filters.
3. *Establish assignment frequency.* Establish the frequency of the assignments. This involves reviewing the equipment condition and records. Normally, the basis for establishing the frequency is the experience of those familiar with the equipment and the recommendations of vendors and

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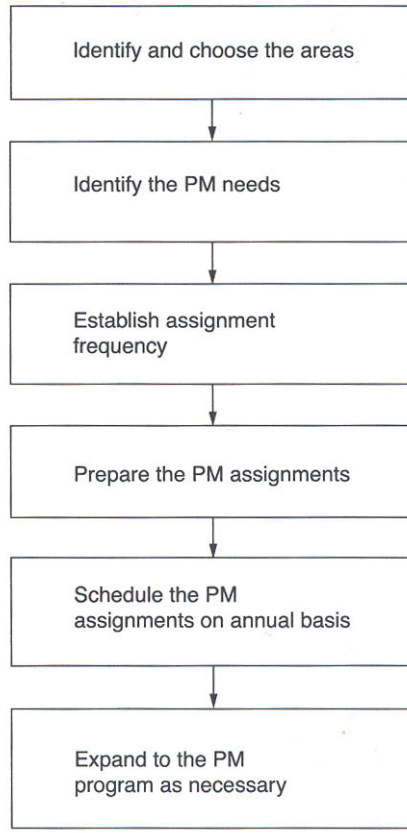
Identify and choose the areas
Identify the PM needs
Establish assignment frequency
Prepare the PM assignments
Schedule the PM assignments on annual basis
Expand to the PM program as necessary

FIGURE 4.2 Six steps for developing a PM program.

engineering. It must be remembered that vendor recommendations are generally based on the typical usage of items under consideration.

4. *Prepare the PM assignments.* Daily and periodic assignments are identified and described in detail, then submitted for approval.
5. *Schedule the PM assignments on annual basis.* The defined PM assignments are scheduled on the basis of a twelve-month period.
6. *Expand the PM program as necessary.* After the implementation of all PM daily inspections and periodic assignments in the initially selected areas, the PM can be expanded to other areas. Experience gained from the pilot PM projects is instrumental to expanding the program.

PM MEASURES

Three important measures of PM are: mean preventive maintenance time (MPMT), median preventive maintenance time (MDPMT), and maximum preventive maintenance time (MXPMT). Each measure is described below.[1]

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Mean Preventive Maintenance Time (MPMT)

MPMT is the average item/equipment downtime needed to conduct scheduled PM. This time does not include PM time expended on the equipment/item during operation or administrative and logistic downtime.

Mean time for PM is defined by

$$\text{MPMT} = \frac{\sum_{i=1}^{m} f_i \text{MPMT}_i}{\sum_{i=1}^{m} f_i} \tag{4.2}$$

where

m = total number of data points,
MPMT_i = mean or average time needed to perform ith preventive maintenance action, for $i = 1, 2, 3, \ldots, m$,
f_i = frequency of ith preventive maintenance action in actions per operating hour after adjustment for equipment duty cycle.

Median Preventive Maintenance Time (MDPMT)

This is the item/equipment downtime needed to carry out 50% of all scheduled preventive maintenance actions on the item/equipment under the conditions outlined for MDPMT. For lognormal distributed PM times, the MDPMT is given by

$$\text{MDPMT} = \text{antilog}\left[\frac{\sum_{i=1}^{m} \lambda_i \log \text{MPMT}_i}{\sum_{i=1}^{m} \lambda_i}\right] \tag{4.3}$$

where

λ_i = constant failure rate of element i of the item/equipment for which maintainability is to be evaluated, adjusted for factors such as duty cycle, tolerance and interaction failures, and catastrophic failures that will lead to deterioration of item/equipment performance to the degree that a maintenance action will be started, for
$i = 1, 2, 3, \ldots, m$.

Maximum Preventive Maintenance Time (MXPMT)

This is the maximum item/equipment downtime required to accomplish a given percentage of all scheduled preventive maintenance actions on the item/equipment under consideration. For lognormal distributed PM times, the MXPMT is given by

$$\text{MXPMT} = \text{antilog}(\log \text{MPMT}_m + yS_{\log \text{MPMT}}) \tag{4.4}$$

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where

y = value from table of normal distribution corresponding to the given percentage value at which MXPMT is defined (e.g., $y = 1.283$ for the 90th percentile and $y = 1.645$ for the 95th percentile). $\log \text{MPMT}_m$ is the mean of logarithms of MPMT_i and is expressed by

$$\log \text{MPMT}_m = \frac{\sum_{i=1}^{m} \lambda_i \log \text{MPMT}_i}{\sum_{i=1}^{m} \lambda_i} \tag{4.5}$$

$$S_{\log \text{MPMT}} = \left\{ \frac{\sum_{i=1}^{m} (\log \text{MPMT}_i)^2 - \left[\left(\sum_{i=1}^{m} \log \text{MPMT}_i \right)^2 \Big/ m \right]}{m-1} \right\}^{1/2} \tag{4.6}$$

PM MODELS

Over the years many PM-related useful mathematical models have been developed. This chapter presents some of those models.

Inspection Optimization Model I

Inspections are often disruptive, but they usually reduce downtime because of lesser number of failures. This model can be used to obtain the optimum number of inspections per facility per unit of time. Total facility downtime is defined by[7,8]

$$\text{TDT} = yT_i + \frac{cT_b}{y} \tag{4.7}$$

where

TDT = total downtime per unit of time for a facility,
c = a constant associated with a particular facility,
T_b = facility downtime per breakdown or failure,
T_i = facility downtime per inspection,
y = number of inspections per facility per unit of time.

By differentiating Eq. (4.7) with respect to y, we get

$$\frac{d\,\text{TDT}}{dy} = T_i - \frac{cT_b}{y^2} \tag{4.8}$$

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By setting Eq. (4.8) equal to zero and then rearranging, we obtain

$$y^* = \left(\frac{cT_b}{T_i}\right)^{1/2} \tag{4.9}$$

where

y^* = optimum number of inspections per facility per unit of time.

By substituting Eq. (4.9) into Eq. (4.7) yields

$$\text{TDT}^* = 2(cT_iT_b)^{1/2} \tag{4.10}$$

where

TDT = total optimal downtime per unit of time for a facility.

Example 4.1

An engineering facility was observed over a period of time and we obtained the following data:

$$T_b = 0.1 \text{ month}, \quad T_i = 0.05 \text{ month}, \quad c = 3$$

Using Eq. (4.9), calculate the optimal number of inspections per month.

Using the given values in Eq. (4.9), we get

$$y^* = \left[\frac{3 \times 0.1}{0.05}\right]^{1/2} = 2.45 \text{ inspections per month}$$

The approximate number of optimal inspections per month is 2.

Reliability and Mean Time to Failure Determination Model of a System with Periodic Maintenance

This mathematical model can be used to calculate the reliability and mean time to failure of a system subject to periodic maintenance. The model is subject to the following assumptions:[9,10]

- A failed part is replaced with a new and statistically identical one.
- Periodic maintenance is performed on the system after every y hours, starting at time zero.

For periodic maintenance, the time interval of y hours is written as

$$y = iY + T, \quad i = 0, 1, 2, \ldots; \; 0 \le T < Y \tag{4.11}$$

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For $i = 1$ and $T = 0$, the reliability of a redundant system subject to periodic maintenance after every Y hours is given by

$$R_Y(y = Y) = R(Y) \tag{4.12}$$

For $i = 2$ and $T = 0$, we have

$$R_Y(y = 2Y) = [R(Y)]^2 \tag{4.13}$$

In this case, the system must operate the first Y hours without experiencing failure. Also, for another Y failure-free hours after the replacement of any failed part.

For $0 < T < Y$, another T hours of system failure-free operation is required. Thus,

$$R_Y(y = 2Y + T) = [R(Y)]^2 R(T) \tag{4.14}$$

In general form Eq. (4.14) is

$$R_Y(y = iY + T) = [R(Y)]^i [R(T)], \quad \text{for } i = 0, 1, 2, 3,\ldots;\ 0 \le T < Y \tag{4.15}$$

The redundant system mean time to failure with the performance of periodic maintenance is given by

$$\text{MTTF}_{\text{pm}} = \int_0^\infty R_Y(y)dy \tag{4.16}$$

To evaluate Eq. (4.16), we write the integral over the range $0 < y < \infty$ as follows:

$$\text{MTTF}_{\text{pm}} = \sum_{i=0}^{\infty} \int_{iY}^{(i+1)Y} R_Y(y)dy \tag{4.17}$$

In Eq. (4.17), the integral of Eq. (4.16) is divided into time intervals of length Y. For $y = iY + T$, by substituting Eq. (4.15) into Eq. (4.17) we get

$$\text{MTTF}_{\text{pm}} = \sum_{i=0}^{\infty} \int_0^Y [R(Y)]^i R(T)dT \tag{4.18}$$

In Eq. (4.18) for $y = iY + T$, $dy = dT$ and the limits become 0 and Y.

Thus, rearranging Eq. (4.18) yields

$$\text{MTTF}_{\text{pm}} = \sum_{i=0}^{\infty} [R(Y)]^i \int_0^Y R(T)dT \tag{4.19}$$

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Since

$$\sum_{i=0}^{\infty}[R(Y)]^i = \frac{1}{1-R(Y)} \tag{4.20}$$

Equation (4.19) becomes

$$\text{MTTF}_{\text{pm}} = \frac{\int_0^Y R(T)dT}{1-R(Y)} \tag{4.21}$$

Example 4.2

Assume that two independent and identical machines form a parallel system. Each machine's times to failure are exponentially distributed with a mean time to failure of 200 h. The periodic preventive maintenance (PM) is performed after every 100 h. Calculate the system mean time to failure with and without the performance of periodic PM.

Using the Chapter 12 information and the given data, the reliability of the two unit parallel system is

$$R(y) = 2e^{-y/200} - e^{-2y/200} \tag{4.22}$$

By substituting Eq. (4.22) into Eq. (4.21) yields

$$\begin{aligned}\text{MTTF}_{\text{pm}} &= \frac{\int_0^{100}(2e^{-T/200} - e^{-2T/200})dt}{1-(2e^{-100/200} - e^{-2(100)/200})} \\ &= \frac{94.17}{0.1548} \\ &= 608.26 \text{ h}\end{aligned}$$

By integrating Eq. (4.22) over the time interval [0, ∞], we get system mean time to failure without the performance of periodic maintenance as follows:

$$\text{MTTF}_{\text{pm}} = \int_0^{\infty}(2e^{-y/200} - e^{-2y/200})dy = 300 \text{ h}$$

This means that periodic PM helped improve the system mean time to failure from 300 to 608.26 h.

Inspection Optimization Model II

This is similar to Inspection Frequency Model I. It can be used to determine optimum inspection frequency in order to minimize the per-unit-of-time equipment/facility downtime. In this model facility/equipment (per-unit time) total downtime is the

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function of inspection frequency. Mathematically, it is defined as follows:[11,12]

$$\begin{aligned} \mathrm{TDT}(n) &= \mathrm{DT}_r + \mathrm{DT}_i \\ &= \frac{\lambda(n)}{\mu} + \frac{n}{\theta} \end{aligned} \tag{4.23}$$

where

$\mathrm{TDT}(n)$ = facility/equipment total downtime per unit of time,
DT_i = equipment/facility downtime due to per-unit-of-time inspection,
DT_r = equipment/facility downtime due to per-unit-of-time repairs,
n = inspection frequency,
$\lambda(n)$ = equipment/facility failure rate,
μ = equipment/facility repair rate,
$1/\theta$ = mean of exponentially distributed inspection times.

By differentiating Eq. (4.23) with respect to n, we get

$$\frac{d\,\mathrm{TDT}(n)}{dn} = \frac{d\,\lambda(n)}{dn}\frac{1}{\mu} + \frac{1}{\theta} \tag{4.24}$$

Setting Eq. (4.24) equal to zero and rearranging yields

$$\frac{d\lambda(n)}{dn} = -\frac{\mu}{\theta} \tag{4.25}$$

The value of n will be optimum when the left and right sides of Eq. (4.25) are equal. At this point the equipment/facility total downtime will be minimal.

Example 4.3

Assume the failure rate of a system is defined by

$$\lambda(n) = f e^{-n} \tag{4.26}$$

where f is the system failure rate at $n = 0$. Obtain an expression for the optimal value of n by using Eq. (4.25).

By substituting Eq. (4.26) into Eq. (4.25), we get

$$-f e^{-n} = -\frac{\mu}{\theta} \tag{4.27}$$

Rearranging Eq. (4.27) yields

$$n^* = \ln\left[\frac{f\theta}{\mu}\right] \tag{4.28}$$

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where

n^* = optimal inspection frequency.

Example 4.4

Assume that in Example 4.3 we have the following:

$$\frac{1}{\mu} = 0.02 \text{ month}, \quad \frac{1}{\theta} = 0.005 \text{ month}, \quad f = 1 \text{ failure per month}$$

Calculate the optimal value of the inspection frequency, n.

Inserting the given values into Eq. (4.28) yields

$$n^* = \ln\left[\frac{1 \times 0.02}{0.005}\right] = 1.39 \text{ inspections per month}$$

This means that roughly one inspection per month will be optimal.

Inspection Optimization Model III

This is a useful mathematical model that can be used to calculate optimum inspection frequency to maximize profit. The model is developed on the premise that the facility/equipment under repair lead to zero output, thus less profit. Furthermore, if equipment is inspected too often, there is danger that it may be more costly due to factors such as loss of production, cost of materials, and wages than losses due to breakdowns. The following assumptions are associated with this model:[11,12]

- The equipment failure rate is a function of inspections.
- Times to inspection are exponentially distributed.
- Equipment failure and repair rates are constant.

The following symbols were used to develop equations for the model:

n = number of inspections performed per unit of time,
$1/\theta$ = mean of exponentially distributed inspection times,
p = profit at no downtime losses,
C_i = average inspection cost per uninterrupted unit of time,
C_r = average cost of repair per uninterrupted unit of time,
λ = equipment failure rate,
μ = equipment repair rate.

Profit per unit of time is expressed by:[11,12]

$$\begin{aligned} \text{PR} &= p - \text{PL}_i - \text{PL}_r - \text{IC} - \text{RC} \\ &= p - \frac{pn}{\theta} - \frac{p\lambda(n)}{\mu} - \frac{nc_i}{\theta} - \frac{C_r\lambda(n)}{\mu} \end{aligned} \tag{4.29}$$

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where

PL_i = production output value loss per unit of time due to inspections,
PL_r = production output value loss per unit of time due to repairs,
IC = inspection cost per unit of time,
RC = repair cost per unit of time.

By differentiating Eq. (4.29) with respect to n and then equating it to zero yield

$$\frac{d\,\mathrm{PR}}{dn} = -\frac{p}{\theta} - \frac{p}{\mu}\frac{d\lambda(n)}{dn} - \frac{C_i}{\theta} - \frac{C_r}{\mu}\frac{d\lambda(n)}{dn} = 0 \tag{4.30}$$

Rearranging Eq. (3.30), we get

$$\frac{d\lambda(n)}{dn} = -\left[\frac{1}{\theta}(p + C_i)\right] \Big/ \left(\frac{p}{\mu} + \frac{C_r}{\mu}\right) \tag{4.31}$$

The value of n will be optimal when left and right sides of Eq. (4.31) are equal. At this point, the profit will be at its maximum value.

Example 4.5

Assume the failure rate of a manufacturing system is defined by Eq. (4.26) in Example 4.3. Develop an expression for the optimal value of n with the aid of Eq. (4.31).

Using Eq. (4.26) in Eq. (4.31) yields

$$-f e^{-n} = -\left[\frac{1}{\theta}(p + C_i)\right] \Big/ \left(\frac{p}{\mu} + \frac{C_r}{\mu}\right) \tag{4.32}$$

By rearranging Eq. (4.32), we get

$$n^* = \ln\left[\frac{f\theta(p + C_r)}{\mu(p + C_i)}\right] \tag{4.33}$$

where

n^* = optimal manufacturing system inspection frequency.

Example 4.6

Suppose that in Example 4.5 we have the following data:

p = \$10,000 per month
f = 2 failures per month
$1/\mu$ = 0.04 month
$1/\theta$ = 0.01 month
C_i = \$75 per month
C_r = \$400 per month

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Determine the optimal value of n by using Eq. (4.33).

By inserting the specified data values into Eq. (4.33), we obtain

$$n^* = \ln\left[\frac{2 \times 0.04 \times (10{,}000 + 400)}{0.01 \times (10{,}000 + 75)}\right]$$
$$= 2.11 \text{ inspections per month}$$

For optimal performance, approximately two inspections per month should be performed.

PM Markov Model

This mathematical model represents a system that can either fail completely or undergo periodic PM. The failed system is repaired. The system transition diagram is shown in Fig. 4.3. The model is useful to predict system availability, probability of system down for PM, and probability of system failure.

The following assumptions are associated with the model:

- System PM, failure, and repair rates are constant.
- After repair or PM the system is as good as new.

The following symbols were used to develop equations for the model:

j = the jth system state, $j = 0$ (system operating normally), $j = 1$ (system failed), $j = p$ (system down for PM),
$P_j(t)$ = probability that the system is in state j at time t, for $j = 0, 1, p$,
λ = system failure rate,
μ = system repair rate,
λ_p = rate of system down for PM,
μ_p = rate of system PM performance.

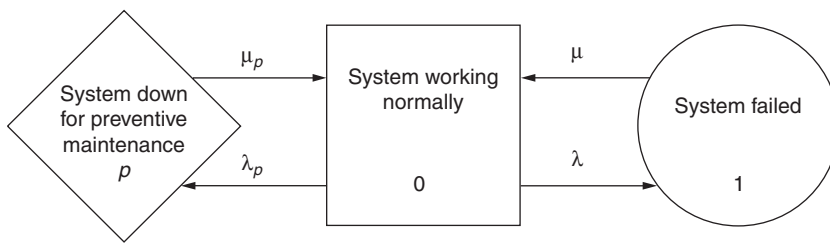

FIGURE 4.3 System transition diagram.

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Using the Markov method we write the following equations for Fig. 4.3:[13]

$$\frac{dP_0(t)}{dt} + (\lambda + \lambda_p) = \mu P_1(t) + \mu_p P_p(t) \tag{4.34}$$

$$\frac{dP_p(t)}{dt} + \mu_p P_p(t) = \lambda_p P_0(t) \tag{4.35}$$

$$\frac{dP_1(t)}{dt} + \mu P_1(t) = \lambda P_0(t) \tag{4.36}$$

At time $t = 0$, $P_0(0) = 1$ and $P_p(0) = P_1(0) = 0$.

Solving Eqs. (4.34)–(4.36), we get

$$P_0(t) = \frac{\mu_p \mu}{m_1 m_2} + \left[\frac{(m_1 + \mu_p)(m_1 + \mu)}{m_1(m_1 - m_2)}\right] e^{m_1 t} - \left[\frac{(m_2 + \mu_p)(m_2 + \mu)}{m_2(m_1 - m_2)}\right] e^{m_2 t} \tag{4.37}$$

$$P_1(t) = \frac{\lambda \mu_p}{m_1 m_2} + \left[\frac{\lambda m_1 + \lambda \mu_p}{m_1(m_1 - m_2)}\right] e^{m_1 t} - \left[\frac{(\mu_p + m_2)\lambda}{m_2(m_1 - m_2)}\right] e^{m_2 t} \tag{4.38}$$

$$P_p(t) = \frac{\lambda_p \mu}{m_1 m_2} + \left[\frac{\lambda_p m_1 + \lambda_p \mu}{m_1(m_1 - m_2)}\right] e^{m_1 t} - \left[\frac{(\mu + m_2)\lambda_p}{m_2(m_1 - m_2)}\right] e^{m_2 t} \tag{4.39}$$

where

$$m_1, m_2 = \frac{-B \pm [B^2 - 4(\mu_p \mu + \lambda \mu_p + \lambda_p \mu)]^{1/2}}{2} \tag{4.40}$$

$$B \equiv (\mu + \mu_p + \lambda + \lambda_p) \tag{4.41}$$

$$m_1 + m_2 = -B \tag{4.42}$$

$$m_1 m_2 = \mu_p \mu + \lambda_p \mu + \lambda \mu_p \tag{4.43}$$

The probability of system failure is given by Eq. (4.38), the probability of system down for PM by Eq. (4.39), and the system availability by Eq. (4.37). As time t becomes large in Eq. (4.37), we get the following expression for the system steady-state availability:

$$\mathrm{AV_{SS}} = \frac{\mu \mu_p}{\mu_p \mu + \lambda_p \mu + \lambda \mu_p} \tag{4.44}$$

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Example 4.7

Assume that in Eq. (4.44) we have $\lambda = 0.005$ failures per hour, $\lambda_p = 0.008$ per hour, $\mu = 0.009$ repairs per hour, and $\mu_p = 0.009$ per hour. Calculate the system steady-state availability.

Substituting the given values into Eq. (4.44) yields

$$AV_{SS} = \frac{0.009 \times 0.009}{(0.009 \times 0.009) + (0.008 \times 0.009) + (0.005 \times 0.009)}$$
$$= 0.4091$$

There is an approximately 41% chance that the system will be available for service. Specifically, the system steady-state availability is 41%.

PM ADVANTAGES AND DISADVANTAGES

The performance of PM has many advantages including increase in equipment availability, performed as convenient, balanced workload, reduction in overtime, increase in production revenue, consistency in quality, reduction in need for standby equipment, stimulation in preaction instead of reaction, reduction in parts inventory, improved safety, standardized procedures, times, and costs, scheduled resources on hand, and useful in promoting benefit/cost optimization.[4,6]

Some disadvantages of PM are: exposing equipment to possible damage, using a greater number of parts, increases in initial costs, failures in new parts/components, and demands more frequent access to equipment/item.[6]

PROBLEMS

1. Discuss at least five important elements of PM.
2. What are the symptoms of a plant in need of a good PM program?
3. What are the important questions that can be asked to determine the adequacy of a PM program?
4. Comment on the principle or formula proposed to decide whether to go ahead with a PM program.
5. List at least ten items whose availability is essential to develop an effective PM program.
6. Discuss important steps for developing a PM program.
7. Discuss the following:
   - Mean PM time
   - Maximum PM time
   - Median PM time
8. Three independent and identical machines form a parallel system. Each machine's times to failure are exponentially distributed with a mean time to failure of 150 h. The periodic PM is performed after every 75 h.

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Determine the system mean time to failure with and without performance of periodic PM.

9. Obtain steady-state expressions for Eqs. (4.38) and (4.39). Obtain an expression for the system steady-state unavailability.
10. What are the benefits and drawbacks of performing PM?

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